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SYMPOSIUM ON THE EARTH: ITS FIGURE, DIMENSIONS AND THE CONSTITUTION OF ITS INTERIOR.

I.

THE INTERIOR OF THE EARTH FROM THE VIEWPOINT OF GEOLOGY.[1]

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(Read April 24, 1915.)

For some time past there has been a marked drift of geologic opinion from the older tenet of a molten earth toward the conviction that the earth is essentially solid. This has been quite as much due to the contributions of kindred sciences as to the growth of geologic evidence, but this has made its important and concurrent contributions.

The great granitic embossments that constitute the most distinctive feature of the oldest known terranes were formerly regarded as solidified portions of a primitive molten earth and seemed to serve as witnesses of the verity of the former liquid state. A few years ago, however, it was determined—almost simultaneously in several countries where critical studies on these formations were

[1] The discussion of this topic at the session of the Society was without manuscript or notes and this paper, prepared some weeks later, is less a reproduction of the original discussion than a substitute for it.

in progress—that these granitic masses are not only intrusive but that they were thrust into formations that had previously been formed at the surface of the earth. These surface formations have thus come to stand as the most ancient terranes now known. These earliest accessible depositions imply the preëxistence of a substantial foundation formed at a still earlier date. Neither of these gives any clear intimation that lower formations are different from themselves. So far then as the record runs back, it testifies to substantial solidity in the outer part of the globe at least. The record implies, indeed, that molten matter was then present within the earth, but it gives no certain measure of the ratio of the molten to the solid part. There is no determinate evidence that a molten condition was a preponderant state, even in the interior, at any stage covered by the lithographic record. The interior conditions of the earliest stages that antedate the lithographic record are to be reached only by indirect and remote rather than direct and immediate inference. Under the influence of inherited presumptions, it may seem to many still probable that the interior of the mature earth was once dominated by a molten condition at some remote stage, but the phenomena of powerful inthrusting, so often shown in the intrusions of the igneous element into the early terranes, seems to imply that at the Archean stages the molten element was in the strong grasp of such stresses as are natural to a rigid globe and was therefore then but a minor and passive factor, not a controlling one.

When it is considered that, if the earth were once wholly molten, the material for all the stratified rocks of later ages must have been derived from the primitive crust after it was formed and forced into positions of erosion—or from matter extruded through it—the absence, according to present knowledge, of any great area of rocks bearing the distinctive characteristics of the congealed surface greatly weakens the assumption that the postulated molten state ever obtained in the mature earth.

A study of the stress-conditions of the interior of the earth seems to call for a similar reversal of the inferences once drawn from the igneous rocks. From the earliest well-recorded ages, the exerior of the earth has given evidence of broad topographic reliefs in the form of great embossments and basins. These surface configurations must have conditioned the localization of extrusions and the deployment of the effusive material. If the lavas arose from a general and abundant source of supply which was responsive to general and powerful stresses, vestiges of this vital relation should be found in the volume and deployment of the lava floods. If, on the other hand, the molten material was but a fraction of the environing mass, variously distributed through it, the result should be a multitude of driblets squeezed out here and there in such special situations as the controlling stresses required, or else forced into weak portions of the earth-body where the stresses were less imperative. Now there is abundant geological evidence that the earth-body has been subjected at repeated intervals to strong compressive stresses by which its outer portion has been folded into mountainous ranges, or pushed up into great plateaus, while masses of continental dimensions have been raised, relatively, to notable heights, and the bottoms of basins and deeps have sunk reciprocally to even greater relative depths. The internal stresses which these deformations imply should have made themselves felt proportionately on any great mass of liquid in the interior—if it were in existence—and extrusions proportionate to the great deformations of the rigid material should have accompanied such diastrophism. But, while liquid extrusions took place somewhat freely at the times of great diastrophism, it was not, at least in my judgment, at all commensurate with the deformative stresses implied by the diastrophic results in the solid material.

Nor was the concentration of the extrusions indicative of origin from a molten interior or from great residual reservoirs of liquid rock. If such ample sources of liquid had existed they might naturally have been expected to have given forth, under the great stresses then seeking easement, correspondingly great floods of lava. Yet no single lava flood seems to have attained more than an extremely small fraction of the mass of the earth or of the known solid matter of its region. Even when the sum total of the most massive series of successive floods in a given region are taken together—though the successive issues stretched over a considerable period—they rarely rise above a most insignificant fraction of earth-mass or even of the regional segment of it with which they are associated. Instead of really massive flows, implying ample sources of supply and great forces of extrusion, the record shows rather a multitude of little ejections or injections of more or less sporadic distribution. The logical implication of these is the preëxistence of a multitude of small liquid spots, or liquifiable spots, scattered widely through the stressed earth-masses and yielding to stress as local conditions required.

This inference is supported by the great variations in altitude at which lavas are given forth. The most impressive illustrations of this are found in current volcanic action whose relations in altitude are precisely known. So far as ancient conditions can be restored, they appear to fall into the same general class as existing conditions. Current outpourings of lava range from the sea bottom to altitudes of many thousands of feet above sea level, a vertical range of several miles. Extrusions occur at these significantly diverse altitudes simultaneously or alternately or in almost any time-relations, and sometimes in the most marked independence of one another in spite of the natural sympathy of such events in a common stressed body. A multitude of facts of detail, some of which are singularly cogent, imply that the lava sources of present volcanoes are disconnected from one another in the interior, and hence independent in action, as a rule, though sometimes they show sympathy without showing liquid connection. The sources of lava seem to be meager in general, and the eruptive agencies seem to be controlled by narrowly local conditions. There is an absence of evidence that the lavas in the craters and necks of volcanoes are parts of great liquid masses below, responsive to the common stresses of a large region.

Thus geological evidence, when critically scrutinized, seems to be distinctly adverse to the existence of even large reservoirs of molten matter within the earth; it points rather to the presence of scattered spots, very small relatively, on the verge of liquefaction, which pass by stages into the liquid form and are then forced out by the differential stresses that abound in the earth body, each such local liquifying center commonly giving forth driblets of lava and gas, at intervals, none of which often rise to more than an extremely minute fraction of the earth mass or even of the subterranean mass contiguous to the volcano.

A revised view of the nature and location of earth-stresses seems also to be required by what is now known of earth-conditions. Under the former dominance of the tenet of a molten globe, it was natural to assign to the stress-differences of the earth a distinctly superficial localization and limitation; they were thought to be affections of "the crust" almost solely. Hydrostatic pressures were of course recognized as affecting the deep interior, but these were obviously balanced stresses, they were ineffective in deformation. The stresses supposed to give rise to the great reliefs of the earth's surface were thought to be very superficial. But the stresses imposed by known deformative agencies are not all superficial, nor are their intensities always greatest at the surface. According to Sir George Darwin, the stress-differences generated in the earth by the tidal forces of the moon are eight times as great at the center of the earth as at the surface. So also, according to the same authority, the stresses engendered by changes in the rotation of the earth are eight times as great at the center as at the surface and are graded between center and surface. The tidal stress-differences are relatively feeble but are perpetually renewed in pulsatory fashion. Those that arise from rotation belong to the highest order of competency. The stress-difference that would arise at the center of the earth from a stoppage of the earth's rotation, would, according to Darwin, reach 32 tons per square inch. Changes of the rate of rotation are almost inevitable when great diastrophic readjustments take place. Such periods are to be regarded as critical times at which great floods of lava should be poured forth from the interior if liquid material were there in great volume ready to respond to the changes of capacity which the deformation of the earth's sectors and the change in the spheroidal form would inevitably impose.

Not to detain you with other considerations, the foregoing seem best to comport with an essentially solid state of the earth's interior, if they do not point rather definitely to such a state. Even if they stood alone, they would seem to make a prevailing solid state the most tenable working hypothesis.

But they are far from standing alone; the geological evidences are strongly supported by considerations that spring from several kindred lines of inquiry. The testimony of astronomic evidence has been given by Dr. Schlesinger. The import of seismic studies, the subject of Dr. Reid's contribution, lends very special support to the view that the interior of the earth is elastico-rigid at least to the extent that distortional waves have been shown to pass through its interior. It seems certain already that this condition prevails throughout much more than half the volume of the earth; concerning the rest, the deep interior, the seismic evidence is perhaps still to be regarded as indeterminate. But on the seismic evidence it does not fall to me to dwell.

The tidal studies of Hecker, Orloff and others lend support to the tenet of a rigid earth but they fall somewhat short of conclusiveness. The brilliant experimental determinations of Michelson and Gale, correlated with the computations of Moulton, have carried the evidence to the point of preliminary demonstration. They need only to be adequately repeated and verified to become final, so far at least as elastic rigidity can be indicated by the response of the earth-body to solar and lunar attractions. The special feature of most critical value in the demonstrations of Michelson and his colleagues is the high degree of elasticity shown by the almost instantaneous response of the earth to the distorting pull of the tide-producing bodies. This cuts at the very base of concepts founded on the supposed properties of a viscous earth. These tidal determinations of elasticity are in close accord with the seismic evidences of elasticity. The two are happily complementary to one another. The one deals with the earth as a whole under rhythmical series of increasing and diminishing stress-differences springing from external attraction; the other deals in an intensive partitive way with earth substance by sharp short stresses that call into action its most intimate structural qualities. While it is wise, no doubt, to refrain from resting too much on these early results of relatively new and radical lines of inquiry, until their results shall be more mature, their prospective import is radical and decisive in favor of a solid earth not only, but of an elastico-rigid earth. Assuming that the present import of these inquiries will be amply justified by more mature research, it is pertinent to bring into consideration the corollary they so distinctly imply, viz.: that the molten and viscous material in the earth, or at least in its outer half, if not throughout its deep interior, is negligible in general studies, and enters into general terrestrial mechanics only as a subsidiary feature. It seems necessary to limit liquid and viscous lacunæ—if there are lacunæ in any proper sense at all—to such moderate dimensions that they do not seriously kill out distortional waves passing through the outer half of the globe in various directions; for seismic instruments show that these waves retain their integrity with surprising tenacity through long traverses. It seems equally necessary to limit the liquid and viscous factor rather severely if the interior structure is to be consistent with so prompt a response of the earth to twelve-hour stress-pulses as to imply almost complete elastic fidelity.

In the light of these determinations, strengthened not a little by their concurrence with the later geological determinations, the working hypotheses of the earth-student can scarcely fail to give precedence to dynamic tenets founded on a rigid earth.

The limitation of liquid and viscous matter, thus imposed, quite radically conditions all tenable views of magmas and of vulcanism, and thus bears upon the igneous nature of the interior. No small part of petrologic effort in past decades has been spent on the differentiation of magmas. To a notable degree these efforts have proceeded on the assumption, conscious or unconscious, that differentiation took its departure from an original homogeneous magma such as might arise from residual portions of a molten earth. Indefinite lapses of time, and such conditions of quiet as are naturally assignable to residual reservoirs of lava, have been freely assumed as working conditions without much question as to their reality. Under the hypothesis of a molten earth passing slowly into a partially solid earth, and retaining residual lacunæ of molten matter as an incident of the change, these assumptions are quite natural. On the other hand, under the hypothesis of a pervasively rigid earth, affected by stress-conditions that are constantly varying in intensity and in distribution—and subject to more radical changes at times of periodic readjustment—the existence of such residual magmas becomes at least questionable, perhaps improbable. Still more questionable is the assumption that the multitude of little liquid spots supposed to arise within the elastico-rigid mass, always have conformed to one type or set of types. The inherent probabilities of the case seem to point strongly to wide variation in nature due to selective solution or differential fusion. The liquefying action that brings magmas into being, under this view, is presumably controlled by the same chemical and physical principles as the solidifying phases of the same cycle. The logical presumption is that at all stages of a magma's career from its inception through its growth, climax and decline to its final solidification, selective action will be in progress more or less and that no stage will be entitled to be regarded as original or parental in a special sense, such a sense for example as might be appropriate if the lava were the residue of an inherited original state and were merely differentiated by fractional crystallization as it passed toward solidification.

While these contrasted views of the history of magmas are naturally connected with views of the genesis of the earth, they are not limited to this relation. They are inherent in the very relations of solid and liquid matter and have a more or less important place irrespective of the earth's genesis.

An element of no small importance to a revised concept of the interior of the earth has arisen from geodetic studies on the distribution of densities within the earth. As the geodetic point of view is to be presented by its foremost exponent, Dr. Hayford, it is permissible for me merely to refer to certain geologic bearings.

On the assumption that the earth was once in a molten state, the inference is unavoidable that a perfect state of isostatic equilibrium was originally assumed by the surface, and that its configuration was at first strictly spheroidal. The material must have been arranged in concentric layers according to specific gravity and each layer should have had the same density at every point. All such reliefs of the earth's surface, and all such differences of specific gravity in the same horizon as have since arisen, must have been superinduced upon this originally perfect isostatic surface. With good reason therefore these inequalities have heretofore been supposed to be relatively shallow. On the hypothesis that the earth grew up by heterogeneous accretions, it is an equally natural inference that differences of specific gravity extend to great depths. In an endeavor to find out the bearings of geodetic data on the distribution of densities, Dr. Hayford tested four assumptions, all of which he found measurably compatible with his geodetic data. From these he derived the respective depths of 37, 76, 109 and 179 miles as the horizons to which differences of density extended and below which they vanished or became negligible. Now all these depths are greater than had been assigned for probable differentiation in the traditional molten earth. On the other hand, the highest figure, 179 miles, was derived from a curve drawn specifically to represent the probable distribution of densities in an earth of planetesimal growth. The distribution represented by this highest figure fits the geodetic data quite as well as either of the other assumptions of distribution, though drawn on a strictly naturalistic basis If it could be said that geodetic data demonstrate that the actual differentiation of specific gravities has its sensible limits somewhere between 37 and 179 miles below the surface, such considerable depth would distinctly favor an accretionary origin as against a molten origin. But a conclusive determination is yet to be reached by geodetic inquiries.

While it is possible, within the broad terms of the planetesimal hypothesis, to suppose that the rate of accretion was so fast as to give rise to a molten planet, such a result seems to me extremely improbable under the actual conditions of the case. The growing planet should have become capable of holding a considerable atmosphere by the time it attained one tenth of its present mass, *i. e.*, about the mass of Mars. After this the protective cushion of the atmosphere should have greatly checked the plunge of the planetesimals and largely dissipated them into dust in the upper atmosphere where the inevitable heat of impact would be promptly radiated away. The dust presumably floated long and came gently to earth, so that, while the total heat generated by impact was large, the temperature of the earth body was probable never very high during the later stages of growth, and perhaps not at any stage of growth. Following out as well as may be the probable rates and conditions of growth, the most tenable concept of the state of the earth's interior under the planetesimal hypothesis is as follows:

The condition of the nuclear portion supposed to be formed from one of the knots of the parent spiral nebula and constituting a minor fraction of the mass of the earth, say thirty or forty per cent., is left indeterminate by present lack of knowledge of the physical state of the knots of spiral nebulæ. If these are gaseous—which is rendered doubtful by their lack of strict sphericity—the nucleus was doubtless originally molten. If the constituents of the knot were held in orbital relations, their aggregation might have been slow enough to permit a solid state of even this portion. The matter added to the nucleus as planetesimal dust, or as planetesimals reduced in mass and speed by the atmosphere, probably retained its solid condition, with negligible exceptions, throughout the process of accretion except as selected portions passed into the liquid state and became subject to extrusive action. An intimate heterogeneity naturally prevailed throughout the whole mass so aggregated. A selective process, however, probably brought in the heavier matter faster and earlier than the lighter matter, for the magnetism of the earth should have aided gravity in gathering in the magnetic metals while the inelastic planetesimals, predominantly the heavy basic ones, when in collision destroyed the opposing components of their motions and hence yielded to the earth's gravity sooner than the more elastic ones. Relatively high specific gravity in the material of the deep interior is thought to have arisen at the outset and to have been increased by the selective vulcanism that came into action as growth proceeded. Special emphasis is laid on the *selective* nature of vulcanism under this hypothesis. The intimate mixture of planetesimals and planesesimal dust gave rise to a multitude of minute contacts between particles of different chemical and physical properties and hence there arose wide differences in the solution points. As the temperature in the growing planet rose, the more soluble portions passed into the liquid state by stages long before the remaining larger portion reached the temperature of solution. In a stressed globe certain of whose stresses are more intense toward the center than toward the surface, the solutions worked in the direction of least resistance, for them generally outwards, carrying heat of liquefaction and leaving the less soluble larger portion behind with temperatures inadequate for further liquefaction until there was a renewed accession of heat. The mechanism thus automatically tended to remove the most soluble constituents by progressive stages, while it tended to preserve the solid condition of the main mass. The hypothesis thus supplies a working mechanism whose results fall into full accord with the states of the interior implied by tidal investigations and by seismic data, while the postulated distribution of specific gravities accords fairly well with geodetic determinations, as they now stand.

The adaptation of such an earth to isostatic adjustment can scarcely be more than hinted at here. The growth of the earth should have given it a concentric structure, while its highly distributive vulcanism, together with some of its deformative processes, should have given a vertical or radial structure, the two conjoining to give a natural tendency to prismatic or pyramidal divisions converging toward the center. The most powerful of all the deformative agencies, rotation, required for the adaptation of the earth to its changes of rate, such divisions of the earth-body as would respond most readily to depression in the polar and bulging in the equatorial tracts reciprocally. As urged elsewhere, this accommodation seems best met by three pyramidal sectors in each hemisphere with apices at the center and bases at the surface, the sectors in opposite hemispheres arranged alternately with one another. Very simple motions of these sectors on their apices at the earth's center would satisfy the larger demands of rotational distortion, while the sub-sectors into which these major sectors would naturally divide, as stresses required, would easily accommodate the nicer phases of adjustment. This primitive segmentation to meet rotational demands—which were most urgent during the stages of infall—furnished a mechanism suitable for the easement also of a portion of the deformational stresses that arose from other sources, among them gravitative stresses arising from loading and unloading by erosion and sedimentation. A gravitational adjustment by the wedging up and down and laterally of such sectors is thus offered tentatively as a working competitor to theories of adjustment by fluidal or quasi-fluidal undertow. The necessary brevity of this statement leaves this new hypothesis little more than a crude suggestion that gravitative adjustment (= isostasy) may perhaps take place as fully as the case requires in a highly rigid elastic earth without resort to flowage or even quasi-flowage.

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